

# Heavy neutrino signals at large hadron colliders

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## Abstract

We study the LHC discovery potential for heavy Majorana neutrino singlets in the process  $pp \rightarrow W^+ \rightarrow \mu^+ N \rightarrow \mu^+ \mu^+ jj$ , plus its charge conjugate. With a fast detector simulation we show that, in contrast with previous claims, backgrounds involving two same-sign muons are not negligible and, moreover, they cannot be eliminated with simple sequential kinematical cuts. Using a likelihood analysis it is shown that, for heavy neutrinos coupling only to the muon, LHC has  $5\sigma$  sensitivity for heavy neutrino masses up to 175 GeV. This reduction in sensitivity, compared to previous parton-level estimates, is driven by the  $\sim 100$  times larger background. Approximate limits are also provided for other lepton number-violating final states, as well as for Tevatron. As a by-product of our analysis, heavy neutrino production has been implemented within the ALPGEN framework.

## 1 Introduction

Large hadron colliders involve strong interacting particles as initial states, giving rise to huge hadronic cross sections. The large luminosities expected will also provide quite large electroweak signals, with, for instance,  $1.6 \times 10^{10}$  ( $4 \times 10^7$ )  $W$  bosons at LHC (Tevatron) for a luminosity of 100 (2)  $\text{fb}^{-1}$ . Therefore, these colliders can be used for precise studies of the leptonic sector, in particular they can produce new heavy neutrinos at an observable level, or improve present limits on their masses and mixings [1,2] (see Ref. [3] for a review). These new fermions transform trivially under the gauge symmetry group of the Standard Model (SM), and in the absence of other interactions they are produced and decay only through their mixing with the SM leptons. Here we will concentrate on this case, neglecting other new production mechanisms, what is a conservative approach. In the presence of new interactions, like for instance in left-right models [4], heavy neutrinos can be also produced by gauge couplings unsuppressed by small mixing angles, yielding larger cross sections and implying a much higher collider

discovery reach [5,6]. In this scenario, however, the observation of the new interactions could be more important than the existence of new heavy neutrinos.

We will concentrate on the first possibility. In this case, for example, it has been claimed by looking at the lepton number violating (LNV)  $\Delta L = 2$  process  $pp \rightarrow \mu^\pm \mu^\pm jj$  that LHC will be sensitive to heavy Majorana neutrinos with masses up to 400 GeV, whereas Tevatron is sensitive to masses up to 150 GeV [1,2]. However, as we shall show, taking into account the actual backgrounds these limits are not realistic. In particular, backgrounds involving  $b$  quarks, as for instance the main one  $t\bar{t}nj$  (with  $nj$  standing for  $n$  additional jets), are two orders of magnitude larger than previously estimated. In this work we make a detailed study, at the level of fast simulation, of the LHC sensitivity to Majorana neutrinos in the process  $pp \rightarrow \mu^\pm \mu^\pm jj$ , which is the most favourable case. The generation of heavy neutrino signals has been implemented in the ALPGEN [7] framework, including the process studied here as well as other final states. In the following, after making precise our assumptions and notation in section 2, we describe the implementation of heavy neutrino production in ALPGEN in section 3 and present our detailed results in section 4. Estimations for Tevatron are given in section 5, and our conclusions are drawn in section 6.

## 2 Heavy neutrino interactions

Our assumptions and notation are reviewed with more detail in Ref. [3] (see also Refs. [8,9]). The SM is only extended with heavy neutrino singlets  $N_j$ , which are assumed to have masses of the order of the electroweak scale, up to few hundreds of GeV. We concentrate on the lightest one, assuming for simplicity that the other extra neutrinos are heavy enough to neglect possible interference effects. The new heavy neutrino  $N$  (where we suppress the unnecessary subindex) can have Dirac character, what requires the addition of at least two singlets, or Majorana, in which case  $(N_L)^c \equiv CN_L^T = N_R$  and lepton number is violated. In either case it is produced and decays through its mixing with the light leptons, which is described by the interaction Lagrangian (in standard notation)

$$\begin{aligned}\mathcal{L}_W &= -\frac{g}{\sqrt{2}} \left( \bar{\ell} \gamma^\mu V_{\ell N} P_L N W_\mu + \bar{N} \gamma^\mu V_{\ell N}^* P_L \ell W_\mu^\dagger \right), \\ \mathcal{L}_Z &= -\frac{g}{2c_W} \left( \bar{\nu}_\ell \gamma^\mu V_{\ell N} P_L N + \bar{N} \gamma^\mu V_{\ell N}^* P_L \nu_\ell \right) Z_\mu, \\ \mathcal{L}_H &= -\frac{g m_N}{2M_W} \left( \bar{\nu}_\ell V_{\ell N} P_R N + \bar{N} V_{\ell N}^* P_L \nu_\ell \right) H.\end{aligned}\tag{1}$$

The SM Lagrangian remains unchanged in the limit of small mixing angles  $V_{\ell N}$ ,  $\ell = e, \mu, \tau$  (which is the actual case), up to very small corrections  $O(V^2)$ . Neutral couplings involving two heavy neutrinos are also of order  $O(V^2)$ . The heavy neutrino mass  $m_N$  joins two different bispinors in the Dirac case and the same one in the Majorana one. Heavy neutrino decays are given by their interactions in Eqs. (1):  $N \rightarrow \ell^- W^+$ ,  $N \rightarrow Z\nu$ ,  $N \rightarrow H\nu$ , plus  $N \rightarrow W^- \ell^+$  for a heavy Majorana neutrino. For  $m_N < M_W$  all these decays are to three body final states, mediated by off-shell  $W$ ,  $Z$  or  $H$  bosons, and have been included in the heavy neutrino ALPGEN extension (see next section). The total width for a Majorana neutrino is twice larger than for a Dirac one with the same couplings [3, 10–12].

As it is apparent from Eqs. (1), heavy neutrino signals are proportional to the neutrino mixing with the SM leptons  $V_{\ell N}$ . Limits on these matrix elements have been extensively discussed previously in the literature, and we quote here only the main results. Low-energy data constrain the quantities

$$\Omega_{\ell\ell'} \equiv \delta_{\ell\ell'} - \sum_{i=1}^3 V_{\ell\nu_i} V_{\ell'\nu_i}^* = \sum_{j=1}^n V_{\ell N_j} V_{\ell' N_j}^*. \quad (2)$$

A global fit to tree level processes involving light neutrinos as external states gives [13, 14],

$$\Omega_{ee} \leq 0.0054, \quad \Omega_{\mu\mu} \leq 0.0096, \quad \Omega_{\tau\tau} \leq 0.016 \quad (3)$$

at 90% confidence level (CL). Note that a global fit without the unitarity bounds implies  $\Omega_{ee} \leq 0.012$  [13]. Additionally, for Majorana neutrinos coupling to the electron the experimental bound on neutrinoless double beta decay requires [15]

$$\left| \sum_{j=1}^n V_{eN_j}^2 \frac{1}{m_{N_j}} \right| < 5 \times 10^{-8} \text{ GeV}^{-1}. \quad (4)$$

If  $V_{eN_j}$  saturate  $\Omega_{ee}$  in Eq. (3), this limit can be satisfied either demanding that  $m_{N_j}$  are large enough, beyond the TeV scale [16] and then beyond LHC reach, or that there is a cancellation among the different terms in Eq. (4), as may happen in definite models [17], in particular for (quasi)Dirac neutrinos.

Flavour changing neutral processes further restrict  $\Omega_{\ell\ell'}$ . The new contributions, and then the bounds, depend on the heavy neutrino masses. In the limit  $m_{N_j} \gg M_W$  [18] they imply

$$|\Omega_{e\mu}| \leq 0.0001, \quad |\Omega_{e\tau}| \leq 0.01, \quad |\Omega_{\mu\tau}| \leq 0.01. \quad (5)$$

Except in the case of  $\Omega_{e\mu}$ , for which experimental constraints on lepton flavour violation are rather stringent, these limits are similar to the limits on the diagonal elements. An

important difference, however, is that (partial) cancellations among loop contributions of different heavy neutrinos may be at work [19]. Cancellations with other new physics contributions are also possible. Since we are interested in determining the heavy neutrino discovery potential and the direct limits on neutrino masses and mixings which can be eventually established, we must consider the largest possible neutrino mixings, although they may require model dependent cancellations or fine-tuning.

### 3 Heavy neutrino production with ALPGEN

For the signal event generation we have extended ALPGEN [7] with heavy neutrino production. This Monte Carlo generator evaluates tree level SM processes and provides unweighted events suitable for simulation. A simple way of including new processes taking advantage of the ALPGEN framework is to provide the corresponding squared amplitudes decomposed as a sum over the different colour structures. In the case of heavy neutrinos this is trivial because there is only one term. This method requires to evaluate from the beginning the squared amplitudes for the processes one is interested in, what is done using HELAS [20]. An alternative possibility which gives more flexibility for future applications is to implement the new vertices at the same level as the SM ones, what is quite more involved.

We have restricted ourselves to single heavy neutrino production. Pair production is suppressed by an extra  $V^2$  mixing factor and by the larger center of mass energy required, what implies smaller PDFs and more suppressed  $s$ -channel propagators. Single heavy neutrino production can proceed through  $s$ -channel  $W$ ,  $Z$  or  $H$  exchange. From these, the first one  $p\bar{p} \rightarrow W \rightarrow \ell N$  is the most interesting process for  $N$  discovery, and has been implemented in ALPGEN for the various possible final states given by the heavy neutrino decays  $N \rightarrow W^\pm \ell^\mp$ ,  $N \rightarrow Z \nu_\ell$ ,  $N \rightarrow H \nu_\ell$  with  $\ell = e, \mu, \tau$ , and for both Dirac or Majorana  $N$ . In the case  $m_N < M_W$  all decays are three-body, and mediated by off-shell  $W$ ,  $Z$  or  $H$ . The transition from two-body to three-body decays on the  $M_W$ ,  $M_Z$  and  $M_H$  thresholds is smooth, since the calculation of matrix elements and the  $N$  width are done for off-shell intermediate bosons. Two approximations are made, however. The small mixing of heavy neutrinos with charged leptons implies that their production is dominated by diagrams with  $N$  on-shell, like those shown in Fig. 1, with a pole enhancement factor, and that non-resonant diagrams are negligible. (Additionally, to isolate heavy neutrino signals from the background one expects that the heavy neutrino mass will have to be reconstructed to some extent.) Then, the only diagrams included are the resonant ones. In the calculation we also neglect light fermion masses

except for the bottom quark.

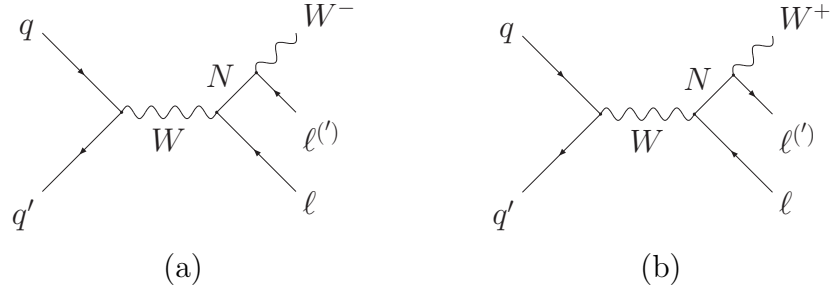


Figure 1: Feynman diagrams for the process  $q\bar{q}' \rightarrow \ell^+ N$ , followed by LNV decay  $N \rightarrow \ell^{(')+} W^-$  (a) and LNC decay  $N \rightarrow \ell^{(')-} W^+$  (b). The diagrams for the charge conjugate processes are similar.

Generator-level results are presented in Fig. 2 for LHC and Tevatron in the relevant mass ranges. Solid lines correspond to the total  $\mu N$  cross sections for  $|V_{\mu N}| = 0.098$ ,  $V_{eN} = V_{\tau N} = 0$ . The dashed lines are the cross sections for the final state  $\mu^\pm \mu^\pm jj$ , which is the cleanest one. The dotted lines are the same but with kinematical cuts

$$\begin{aligned}
 \text{LHC : } & p_T^\mu \geq 10 \text{ GeV}, \quad |\eta^\mu| \leq 2.5, \quad \Delta R_{\mu j} \geq 0.4, \\
 & p_T^j \geq 10 \text{ GeV}, \quad |\eta^j| \leq 2.5, \\
 \text{Tevatron : } & p_T^\mu \geq 10 \text{ GeV}, \quad |\eta^\mu| \leq 2, \quad \Delta R_{\mu j} \geq 0.4, \\
 & p_T^j \geq 10 \text{ GeV}, \quad |\eta^j| \leq 2.5,
 \end{aligned} \tag{6}$$

included to reproduce roughly the acceptance of the detector and give approximately the “effective” size of the observable signal. Of course, the correct procedure is to perform a simulation, as we do in next section, but for illustrative purposes we include the cross-sections after cuts. In particular, they clearly show that although for  $m_N \leq M_W$  the total cross sections grow several orders of magnitude, both at LHC and Tevatron, partons tend to be produced with low transverse momenta (the two muons and two quarks result from the decay of an on-shell  $W$ ), making the observable signal much smaller. These results are in agreement with those previously obtained in Ref. [2].

## 4 Di-lepton signals at LHC

### 4.1 $\mu^\pm \mu^\pm jj$ production

We analyse in detail the case of a Majorana neutrino coupling only to the muon, which is, as it has already been emphasised, the situation in which LHC has better discovery

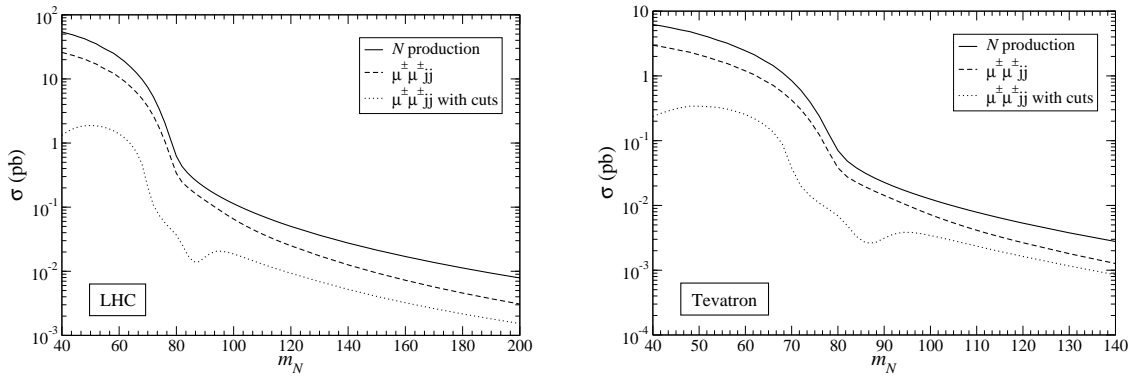


Figure 2: Cross sections for heavy neutrino production at LHC (left) and Tevatron (right), as a function of the heavy neutrino mass, for  $|V_{\mu N}| = 0.098$ . The solid lines correspond to total  $\mu N$  cross section, the dashed line includes the decay to same-sign muons and the dotted line is the same but including the kinematical cuts in Eq. (6).

prospects than ILC [12]. The most interesting final state is  $\mu^\pm \mu^\pm jj$ , with two same sign muons and at least two jets. Since this LNV signal has sometimes been considered [1,2] to be (almost) background free, a realistic and detailed discussion of the actual backgrounds is worthwhile. A first group of processes involves the production of additional leptons, either neutrinos or charged leptons (which may be missed in the detector). The main ones are  $W^\pm W^\pm nj$  and  $W^\pm Znj$ , where  $nj$  stands for  $n = 0, 1, 2, \dots$  additional jets. We point out that not only the processes with  $n = 2$  contribute: processes with  $n < 2$  are backgrounds due to the appearance of extra jets from pile-up, and processes with  $n > 2$  cannot be cleanly removed because of pile-up on the signal. A second group includes final states with  $b$  and/or  $\bar{b}$  quarks, like  $t\bar{t}nj$ , with semileptonic decay of the  $t\bar{t}$  pair, and  $Wb\bar{b}nj$ , with  $W$  decaying leptonically. In these cases the additional same-sign muon results from the decay of a  $b$  or  $\bar{b}$  quark. Only a tiny fraction of such decays produce isolated muons with sufficiently high transverse momentum. But, since the  $t\bar{t}nj$  and  $Wb\bar{b}nj$  cross sections are so large, these backgrounds are also much larger than backgrounds with two weak gauge bosons. (Also,  $b\bar{b}nj$  production could result in a large background but both muons have small  $p_T$  in this case, and it can be eliminated by requiring a large reconstructed neutrino mass together with a large  $\mu\mu$  invariant mass, as we do below.) An important remark here is that the corresponding backgrounds  $t\bar{t}nj, Wb\bar{b}nj \rightarrow e^\pm e^\pm X$  are one order of magnitude larger than the ones involving muons. The reason is that  $b$  decays produce “apparently isolated” electrons more often than muons, because electrons are detected in the calorimeter while muons travel to the muon chamber. A reliable evaluation of the  $e^\pm e^\pm X$  background resulting from these processes seems to require a full simulation of the detector.

We have generated the signal and backgrounds using ALPGEN and passing them through PYTHIA 6.4 [21] with the MLM prescription [22] to avoid double counting of jet radiation. A fast simulation of the ATLAS detector [23] has been performed. We have taken  $m_N = 150$  GeV and  $V_{\mu N} = 0.098$ . The pre-selection criteria are:

- (i) two same-sign isolated muons with pseudorapidity  $|\eta| \leq 2.5$  and transverse momentum  $p_t$  larger than 10 GeV, and no additional isolated charged leptons;
- (ii) no additional non-isolated muons;
- (iii) two jets with  $|\eta| \leq 2.5$  and  $p_t \geq 20$  GeV.

It must be noted that the requirement (ii) reduces the backgrounds involving  $Z$  bosons by almost a factor of two, and thus proves to be quite useful. The number of events at LHC for  $30 \text{ fb}^{-1}$  after pre-selection cuts is given in Table 1. Additional backgrounds such as  $t\bar{t}4j$ ,  $t\bar{t}5j$ ,  $ZZnj$ ,  $WWZnj$ ,  $WZZnj$ ,  $ZZZnj$  are smaller and we do not show them, but they are included in the estimation of the signal significance below. Backgrounds with a Higgs boson, like  $WH$  and  $ZH$ , have much smaller cross sections than those giving the same four fermions in the final state and gathered in Table 1.

|               | Pre-selection |         |         |         | Selection |         |         |         |
|---------------|---------------|---------|---------|---------|-----------|---------|---------|---------|
|               | $n = 0$       | $n = 1$ | $n = 2$ | $n = 3$ | $n = 0$   | $n = 1$ | $n = 2$ | $n = 3$ |
| $\mu N$       | 92.9          | —       | —       | —       | 38.3      | —       | —       | —       |
| $t\bar{t}nj$  | 747.8         | 730.3   | 405.0   | 240.9   | 0.9       | 0.3     | 0.3     | 0.0     |
| $Wb\bar{b}nj$ | 53.9          | 254.9   | 232.5   | 222.5   | 0.0       | 0.1     | 0.2     | 0.1     |
| $Zb\bar{b}nj$ | 12.5          | 27.5    | 14.8    | 13.0    | 0.0       | 0.0     | 0.0     | 0.0     |
| $WWnj$        | ×             | ×       | 116.2   | 200.2   | ×         | ×       | 1.5     | 0.8     |
| $WZnj$        | 57.7          | 156.1   | 244.8   | 156.9   | 0.2       | 0.9     | 2.9     | 0.8     |
| $WWWnj$       | 13.3          | 23.8    | 26.8    | 18.4    | 0.2       | 0.5     | 0.0     | 0.0     |

Table 1: Number of  $\mu^\pm\mu^\pm X$  events at LHC for  $30 \text{ fb}^{-1}$ , at the pre-selection and selection levels. The heavy neutrino signal is evaluated assuming  $m_N = 150$  GeV and  $V_{\mu N} = 0.098$ . Processes which do not contribute due to electric charge conservation are marked with a cross. Signal contributions with extra jets not available at the generator level are marked with a dash.

The fast simulation shows that SM backgrounds are about two orders of magnitude larger than previously estimated. Moreover, they cannot be sufficiently suppressed with respect to the heavy neutrino signal using simple cuts. Some obvious discriminating variables, plotted in Fig. 3, are:

- The missing momentum  $\cancel{p}_t$ : it is smaller for the signal because it does not have neutrinos in the final state.
- The separation between the muon with smallest  $p_T$  (we label the two muons as  $\mu_1, \mu_2$ , by decreasing transverse momentum) and the closest jet,  $\Delta R_{\mu_2 j}$ . For backgrounds involving  $b$  quarks this separation tends to be rather small.
- The transverse momentum of the two muons,  $p_T^{\mu_1}$  and  $p_T^{\mu_2}$ , respectively. In particular  $p_T^{\mu_2}$  is a good discriminant against backgrounds from  $b$  quarks, because these typically have one muon with small  $p_T$ .

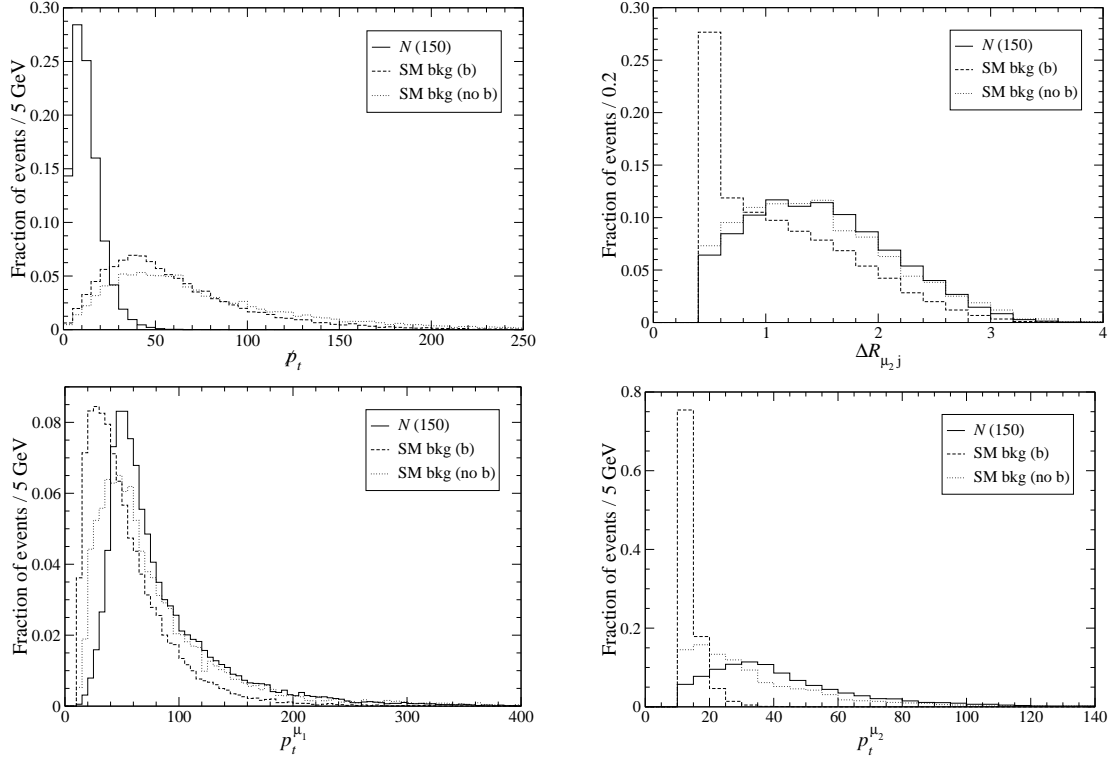


Figure 3: Normalised distributions of several discriminating variables for the signal and the backgrounds with and without a muon from a  $b$  quark (see the text).

Kinematical cuts on them do not render the  $\mu^\pm\mu^\pm jj$  final state “background-free”, as it is apparent from the plots (and we have explicitly confirmed). Indeed, for the large background cross sections in Table 1 the overlapping regions contain a large number of background events, and background can only be eliminated by severely reducing the signal. However, a likelihood analysis using these and several other variables can efficiently reduce the background. Additional relevant variables are shown in Fig. 4:



- The invariant mass of  $\mu_2$  (the muon with lowest  $p_T$ ) and the two jets which best reconstruct the  $W$  boson,<sup>1</sup>  $m_{\mu_2 W}$ . An important observation in this case is that in backgrounds involving  $b$  quarks this muon typically has a small  $p_t$ , displacing the background peak to lower invariant masses.
- The invariant mass of the two muons
- The number of  $b$ -tagged jets  $N_b$  and jet multiplicities  $N_j$ . Especially the former helps to separate the backgrounds involving  $b$  quarks because they often have  $b$ -tagged jets.
- The transverse momenta of the jet with maximum and second maximum  $p_T$ , respectively  $p_T^{\max}$  and  $p_T^{\max 2}$ .

These variables are not suited for performing kinematical cuts but greatly improve the discriminating power of a likelihood function. Three additional variables, less important and hence not shown for brevity, are the angles between the  $W$  and the muons and the pseudorapidity of the muon which best reconstructs the heavy neutrino mass. The resulting log-likelihood function is also shown in Fig. 4, where we distinguish three likelihood classes as in the previous figures: the signal, backgrounds with one muon from  $b$  decays, and backgrounds with both muons from  $W/Z$  decays.

As selection criteria we require  $\log_{10} L_S/L_B \geq 1.75$  and that at least one of the two heavy neutrino mass assignments  $m_{\mu_1 W}$ ,  $m_{\mu_2 W}$  is between 130 and 170 GeV.<sup>2</sup> The number of events surviving these cuts can be read on the right block of Table 1. As it is apparent, the likelihood analysis is quite effective in suppressing backgrounds, especially  $t\bar{t}nj$  and  $W/Zb\bar{b}nj$ . Assuming a “reference” 20% systematic uncertainty in the backgrounds (which still has to be precisely evaluated), the resulting statistical significance for the heavy neutrino signal is of  $9.9\sigma$ . Heavy neutrino masses up to

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<sup>1</sup>The reconstruction of the  $W$  boson from two jets is done trying all possible pairings among the four jets with maximum  $p_T$ . This is done to ensure a good reconstruction of the heavy neutrino mass in the presence of pile-up, which gives several additional jets in each event and prevents from reconstructing the  $W$  naively, *e.g.* using the two jets with highest  $p_T$ . Although this procedure provides a good  $m_N$  reconstruction, the  $W$  reconstructed mass is no longer an useful discriminating variable. Indeed, background events quite often have two jets with invariant mass  $\sim M_W$ . In order to further improve the reconstruction, the two jet momenta are rescaled so that their invariant mass coincides with  $M_W$ .

<sup>2</sup>The latter requirement assumes a previous knowledge of  $m_N$ , in the same way as the signal distributions for the likelihood analysis are built for a precise  $m_N$  value. Thus, experimental searches must be performed by comparing data with Monte-Carlo samples generated for different values of  $m_N$ . This procedure, although more involved than a search with generic cuts, provides much better sensitivity.

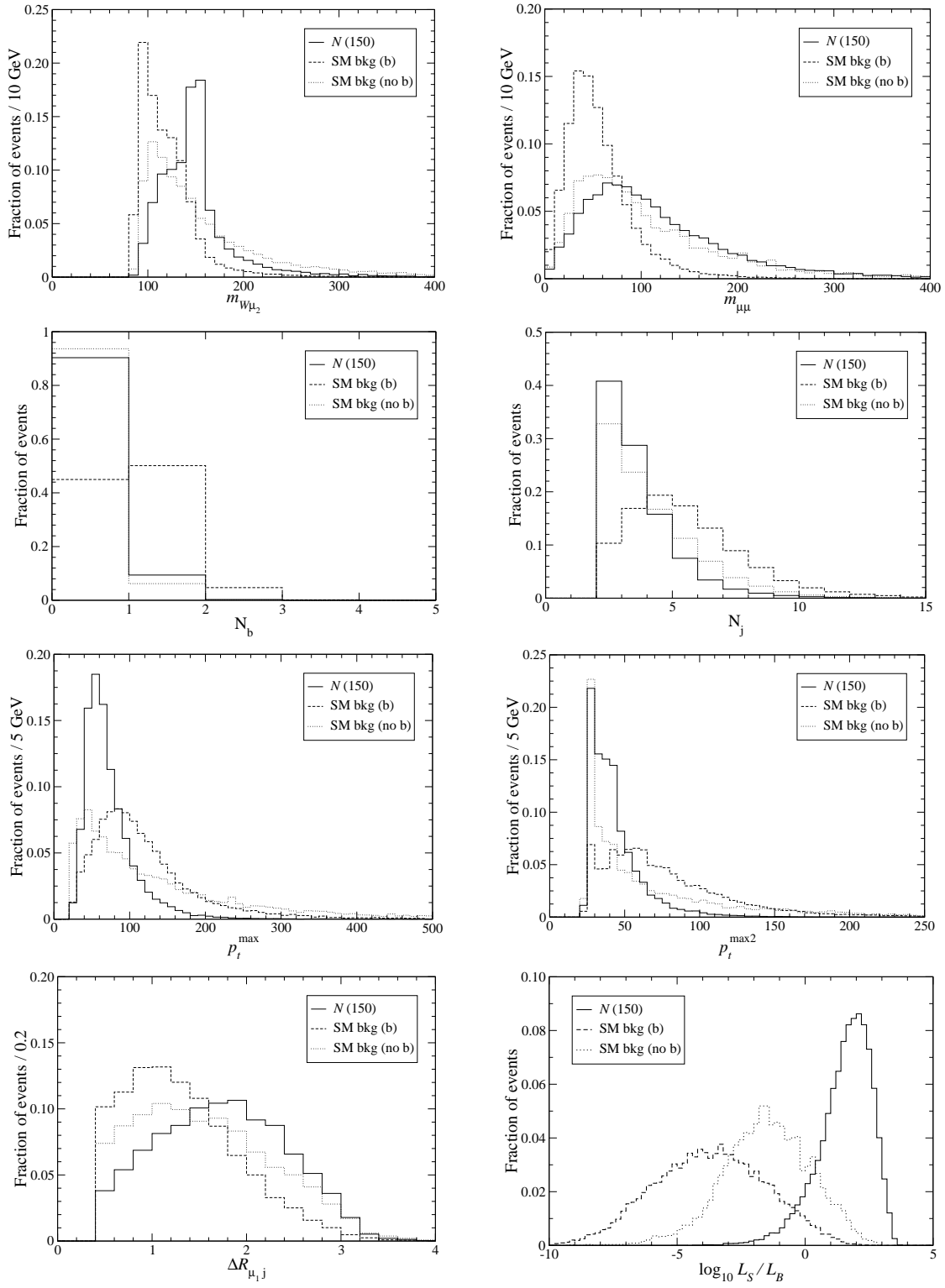


Figure 4: Normalised distributions of several discriminating variables for the signal and the backgrounds with and without a muon from a  $b$  quark (see the text). The last plot corresponds to the log-likelihood function.

175 GeV can be observable with  $5\sigma$  at the LHC for  $V_{\mu N} = 0.098$ . These figures can be considered conservative because only the lowest-order signal contribution (without extra jets) has been included. Further signal contributions  $\mu N nj$  should improve the heavy neutrino observability. If the Higgs is heavier than 120 GeV the branching ratio  $\text{Br}(N \rightarrow W\mu)$  will also increase.

## 4.2 Other same-sign dilepton signals

In final states  $e^\pm e^\pm$ ,  $e^\pm \mu^\pm$  the analysis is similar but the backgrounds are larger, as it has been pointed out before. In fact, it seems likely that a reliable estimation of the  $e^\pm e^\pm$ ,  $e^\pm \mu^\pm$  backgrounds from  $t\bar{t}nj$  and  $W/Zb\bar{b}nj$  production requires a very good knowledge of the detector, that is, a full simulation. However, with the results in the previous section one may still attempt to provide approximate limits for these two channels, before a complete and lengthy analysis is done.

For a heavy neutrino coupling only to the electron we assume a reference value  $V_{eN} = 0.073$  and  $V_{\mu N} = V_{\tau N} = 0$ , and consider  $e^\pm e^\pm$  final states. We take the  $t\bar{t}nj$ ,  $W/Zb\bar{b}nj$  backgrounds as ten times larger than the corresponding ones involving muons, as it is found with fast detector simulation. The  $ZWnj$  ones are estimated to be 1.7 times larger, corresponding to the effect of the pre-selection requirement of no non-isolated muons, which has no analogous for electrons. The  $WWnj$  and  $WWWnj$  backgrounds should be of the same size. With this rescaling of the backgrounds in Table 1 and the mass dependence of the cross sections in Fig. 2, we estimate that for  $V_{eN} = 0.073$  it is possible to have  $5\sigma$  significance up to masses  $m_N \simeq 130$  GeV.

For a heavy neutrino coupling to both electron and muon, we assume for definiteness  $V_{eN} = 0.073$ ,  $V_{\mu N} = 0.098$ ,  $V_{\tau N} = 0$  (see section 2, however). The procedure followed to extract limits is the same, but considering the various production and decay possibilities. Adding the statistical significances of the three channels  $e^\pm e^\pm$ ,  $\mu^\pm \mu^\pm$  and  $e^\pm \mu^\pm$ , and rescaling from the cross sections in Fig. 2, we find  $5\sigma$  significance up to masses  $m_N \simeq 160$  GeV.

## 5 Estimates for Tevatron

The observability of heavy neutrino signals in same-sign dilepton channels at Tevatron seems to be dominated by the size of the signal itself. In contrast with LHC, backgrounds are much smaller. For example, the  $WZjj$  and  $WWjj$  backgrounds have cross sections of 0.1 and 0.09 fb, respectively, with the cuts in Eq. (6). Since these

backgrounds turn out to be the most dangerous ones at LHC (after the likelihood cut), it seems reasonable to estimate the total background for  $1 \text{ fb}^{-1}$  as one event. Thus, if signal events have not been observed with the already collected luminosity, upper limits of 3.36 and 4.14 events [24] can be set on the signal, at 90% and 95% confidence level (CL), respectively. For a fixed mass  $m_N = 60 \text{ GeV}$ , from Fig. 2 this implies upper bounds  $|V_{\mu N}| \leq 1.3 \times 10^{-4}$  (90% CL)  $|V_{\mu N}| \leq 1.6 \times 10^{-4}$  (95% CL). This would improve the limits from L3 [25, 26]. Of course, a detailed simulation with the already collected data is necessary to make any claim, and the limits eventually obtained will depend on the actual number of observed same-sign dilepton events.

Note also that, given the cross sections in Fig. 2, for a luminosity of  $1 \text{ fb}^{-1}$  and  $V_{\mu N} = 0.098$  the heavy neutrino signals only exceed one event for heavy neutrino masses  $m_N \leq M_W$ , thus the Tevatron sensitivity is limited to this mass range.

## 6 Conclusions

Large hadron colliders are not in principle the best place to search for new heavy neutral leptons. However, Tevatron is performing quite well and LHC will start operating in few months, so one must wonder if the large electroweak rates available at large hadron colliders allow to discover new heavy neutrinos, given the present constraints on them, or improve these constraints. This is indeed the case in models with extra interactions [5, 6]. In this work we have, however, assumed that no other interactions exist and that heavy neutrinos couple to the SM particles through its small mixing with the known leptons.

Heavy Dirac or Majorana neutrinos with a significant coupling to the electron can be best produced and seen at  $e^+e^-$  colliders in  $e^+e^- \rightarrow N\nu$ , which has a large cross section and whose backgrounds have a moderate size [10, 12, 19, 27]. On the contrary, a Majorana  $N$  mainly coupled to the muon is easier to discover at a hadronic machine like LHC, in the process  $q\bar{q}' \rightarrow W^+ \rightarrow \mu^+N$  with subsequent decay  $N \rightarrow \mu^+W \rightarrow \mu^+q\bar{q}'$  (plus the charge conjugate). However, even this LNV final state is not easy to deal with. SM backgrounds are large and require a careful analysis, especially those involving  $b$  quarks, for example  $t\bar{t}nj$  which is the largest one.

For the simulation of the  $\mu^\pm\mu^\pm jj$  signal process (and other heavy neutrino decay channels which have not been studied in detail here) we have implemented heavy neutrino production in the ALPGEN framework. We have then shown, using a fast detector simulation, that a heavy neutrino with a mixing  $V_{\mu N} = 0.098$  can be discovered with  $5\sigma$  significance up to masses  $m_N = 175 \text{ GeV}$ . This is in sharp contrast with

previous estimations, and corresponds to a increase in the background of about two orders of magnitude.

Based on our detailed calculation for the  $\mu^\pm\mu^\pm jj$  final state, we have estimated that a heavy neutrino only coupling to the electron with  $V_{eN} = 0.073$  can be discovered up to  $m_N = 130$  GeV. For a neutrino coupling simultaneously to both electron and muon, taking for reference the values  $V_{\mu N} = 0.098$ ,  $V_{eN} = 0.073$ ,  $V_{\tau N} = 0$ , the limit would be about  $m_N = 160$  GeV. LNC final states have larger backgrounds, for example,  $e^\pm\mu^\mp jj$  (for which  $t\bar{t}nj$  is a much more dangerous background) and especially when lepton flavour is also conserved, as in  $\mu^\pm\mu^\mp jj$ . Hence, LHC is not expected to provide any useful direct limit on heavy Dirac neutrinos, for which all final states conserve lepton number. By the same token, other decay channels such as  $N \rightarrow Z\nu$ ,  $N \rightarrow H\nu$  and production processes as  $pp \rightarrow Z \rightarrow N\nu$ , have too large backgrounds as well.

It is finally worth emphasising that larger effects due to heavy neutrinos and, more generally, other neutrino physics beyond the SM may be observed at large hadron colliders. However, in all cases they require new interactions and often model dependent constraints. This means further assumptions, and in this situation the main novel ingredient is not only the heavy neutrino. In this category there are many interesting scenarios, also including supersymmetry (see for an example Refs. [28, 29]). Then, compared to these new physics models the limits established in this work are modest. For example, if the heavy neutrino has an interaction with a typical gauge strength, as in the case of left-right models with a new heavy  $W_R$ , the LHC reach for  $m_N$  increases up to approximately 2 TeV [5, 6].

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